VARIABILITY OF THE SOLAR RESOURCE AND GRID OPERATION IMPACTS

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ABSTRACT: The interaction and coordination between On-Load Tap Changer (OLTC), capacitor, and inverter operations for increased PV penetration and varying operational scenarios are a concern of many transmission and distribution system operators, but is not normally considered part of the interconnection study. Long term variability impacts of variable resources on regulation equipment must be quantified to reach mandated renewable penetration levels, and maintain security of supply. This issue is generally not a problem for single distribution sites, but when a large cluster or node of sites experiences highly variable cloud cover, there could be increased tap changer operations, and other adverse impacts. Renewable generation is growing at a rapid rate due to the incentives available and the aggressive renewable portfolio standard (RPS) targets implemented by state governments. The High Penetration PV (HiP-PV) project on Oahu aims to understand the effects of high penetration PV on the distribution level, to identify penetration levels creating disturbances on the circuit, and to offer mitigating solutions based on model results. This paper evaluates the variability of the solar resources based on a one year measured dataset from Hawaii on the island of Oahu and presents a preliminary study into voltage regulation impacts for a large distribution level PV site.
Keywords: see enclosed list of keywords

1. INTRODUCTION

Solar PV systems have evolved from small stand-alone systems through small residential and commercial systems to large systems and clusters of systems that provide significant distributed energy onto the utility grid. At high PV penetration levels, due to the lack of utility visibility to these resources, there is an emerging need to quantify and plan for new challenges for the managing these resources and their variability impacts on the rest of the grid. Managing the variability of weather-dependent renewable resources such as solar for grid operation is an emerging area of work [1].

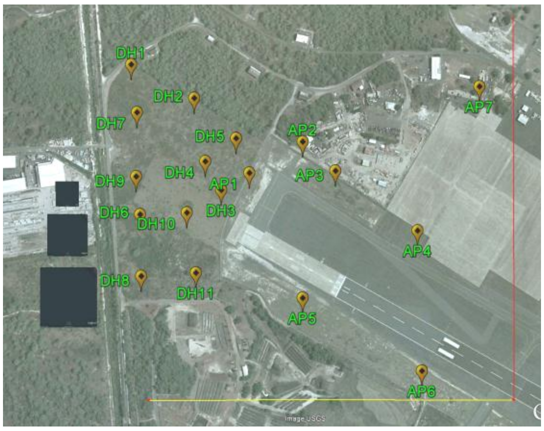


Figure 1: A network of 17 solar radiation sensors has been installed by NREL at Oahu, Hawaii. The 1 second time resolution data set covered the time from April 2010 until March 2011. The red and yellow lines indicate a 1km x 1km grid. The black squares on the left represent different sizes of PV systems from 100 kWp to 1 MWp.

To inform industries activities, this paper evaluates the variability of the solar resources based on a one year measured dataset from Hawaii on the island of Oahu. The high resolution dataset (spatial resolution 100m to 10km and temporal resolution of 1 second) was based on a temporary 17-sensor monitoring deployment by the National Renewable Energy Laboratory (NREL) with funds from the US Department of Energy [2].

Results discussed in this paper translate the solar resource dataset and variability into utility impacts on the grid during different grid states or operational conditions. The paper adds to a better understanding of the three domains of “Meteorology”, “Solar Energy” and “Distributed Network Operation” which need a better integration of needs and data to ensure reliable grid operation especially at higher penetration of solar energy on the electricity network.

2. BACKGROUND

The High PV Penetration Project [3], implemented in June 2010, addresses common issues between the Sacramento Municipal Utility District (SMUD) and the Hawaiian Electric Utility (HECO). Both utilities adopted aggressive renewable energy targets with SMUD targeting 37% by 2020 and HECO targeting 40% by 2030 for the three Hawaiian utilities [3]. In conjunction with HiP-PV, the National Renewable Energy Laboratory (NREL) funded a collaborative effort together with Hawaiian Electric Company (HECO). These studies aim to characterize impacts of high PV penetrations on different types of distribution feeders and inform future interconnection processes.

The traditional distribution system is designed to deliver power from generator to customer load and therefore all the control and protection equipment on the system are designed to move generation to load. Now, local load centers can generate sufficient power to service the local needs.

Lessons learned to date include;

- Availability of measured data is key to fully understanding impacts and sustainable development
- Software integration is essential for maintaining growing PV portfolio
- Utilities must prepare for high penetrations of variable resources and get ahead of the curve
- Legacy and aging distribution equipment, such as load tap changers, are particularly impacted by variability of high PV penetrations
- Utilities must plan for upgrades and operational changes ahead of time, with informed and validated analysis
- All stakeholders (i.e. operations, transmission and distribution planning, government agencies and developers) must find common ground for continued sustainable development

3. METHODOLOGY

The ramp rates of 20 precisely time-synced solar radiation sensors are evaluated in the time domain from 1 second up to 60 minutes. These time domains are of interest as different operational controls and decisions in this time period may be affected by short-term and hourly solar variability. The local setup of the sensors enabled detailed analysis of averaging in space and correlation of impacts in time. Monthly linear cross correlation of ramp rates for 17 sensors within a grid of 1km x 1km has been investigated. The results have been used to show potential impact of variable solar power to the different control and operation devices within the distribution grid.

The impact of the variability of the solar resource with respect to averaging in space and time has been evaluated thus far mainly based on a very limited amount of measured data. The setup of 17 sensors within a 1 km x 1 km region and several additional sensors in the surrounding serves as a good proxy for modelling clusters of distributed generation. Thus the work looked at using this information to evaluate smoothing effects in space and time, based on real measurements and better understand the micro-climates, nature of geographic diversity and impact of smoothing of this variable energy source and its impact to the control and operation of the distribution grid with clusters of distributed generation.

Grid modelling with integrated variability analysis for distributed resources is an essential piece to understanding the high penetration impacts. Under feed-in-tariff ("FIT") programs, eligible renewable energy projects can produce power to sell back to utilities. As more of the local, distributed generation is expected to come from variable, non-dispatchable PV resources, utilities and HECO need to better plan contributions from non-dispatchable local generation. Visibility and monitoring of these non dispatchable resources is an essential piece of the future planning process.
Though many issues are analyzed through the high PV process, this particular analysis focuses on the input of 17 sensor data grid, to a grid model, and the resulting impact on voltage and regulation equipment impacts. A realistic grid model of an area of the HECO distribution system is used with a detailed tap changer model to quantify the probability of these impacts increasing the number of cycles the tap changer experiences.

In general maintenance is performed on OLTC's based on the individual operating conditions, usually within the range of 20000 to 100000 operations, or approximately every 4 years. On average OLTC's are expected to perform on average 5000 operations per year [6]. An increase in the number of operations will increase the time to operations and maintenance and therefore cost of the OLTC over its lifetime, and therefore any increase attributed to variable resource integration should be evaluated.

4. RESULTS

4.1 Resource Variability Analysis

For this location, the frequency distributions of 1 second ramp rates from 17 sensors show a high correlation (Figure 2). Within this set of sensors between 357 and 573 (average 417) events per year show 1 second ramps higher than 500 Watt/sqm, reflecting a > 50% change in power within one second.

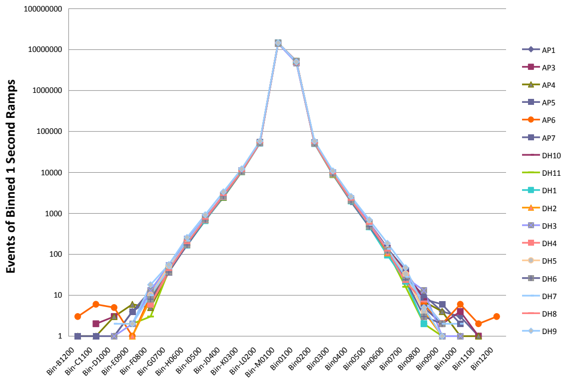


Figure 2: Frequency distribution of 1 second ramps from 17 sensors at the test site on the island of Oahu show quite similar behavior. In average 417 events per year show a ramp higher than 500 Watt/sqm.

The monthly results show different seasons with higher (March to August) and lower (Sept-Feb) ramp activity.

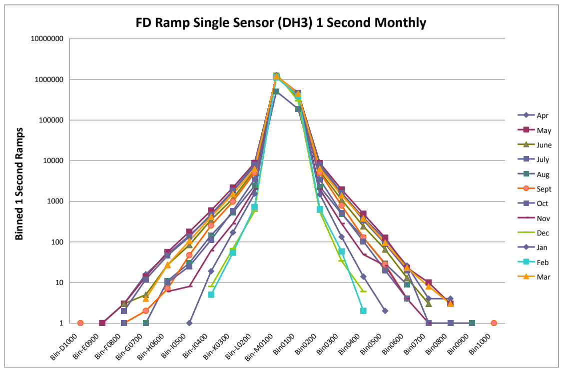


Figure 3: Monthly frequency distribution of 1 second ramps from 1 single sensor. Higher variability in Summer an

Averaging of 2 to 17 sensors leads to significant reduction of ramp rates in the timescale of 1 to 60 seconds, and shows almost no influence in the time domain of 10min to 60min. The monthly cross correlation of 1 second ramp rates has a high reduction up to 1 km after which if flattens. Measured increased activity of tap changers is in good correlation with the variability evaluation of the solar resource. The work also showed that regional microclimates need to also be well monitored as information derived from one geographic region on ramps and smoothing will not apply in another cluster region.

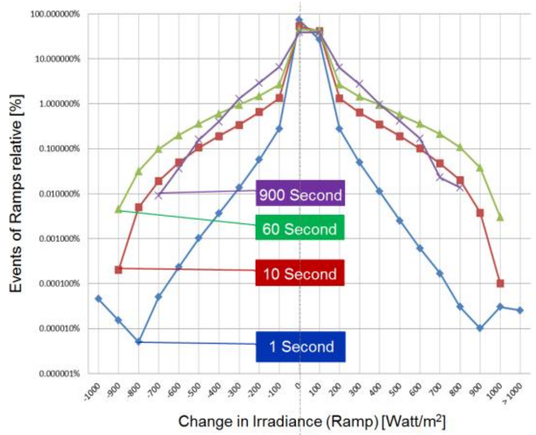


Figure 4: Cumulative frequency distribution of ramps over one year at one site show clear differences in the different time domains.

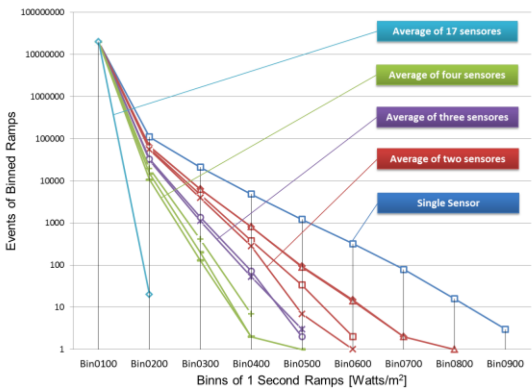
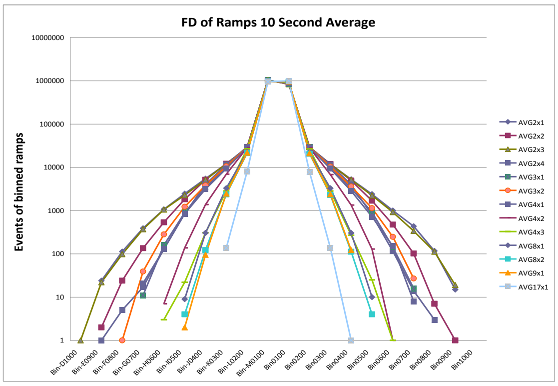
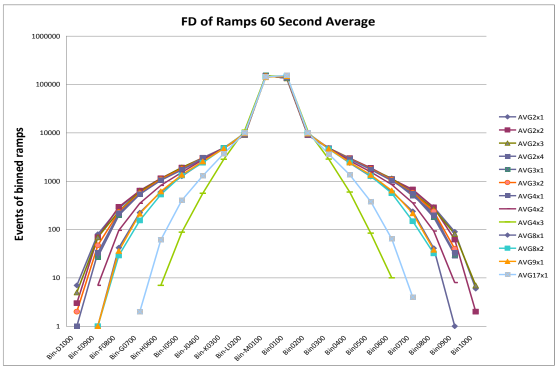
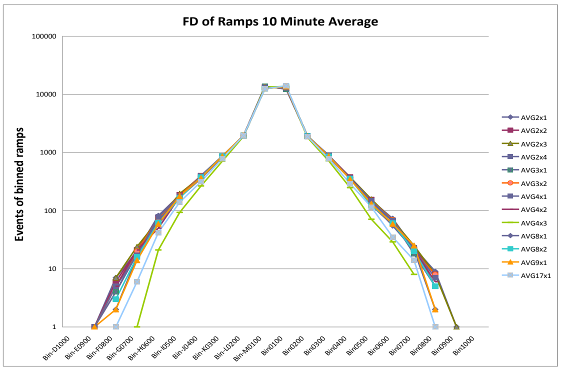


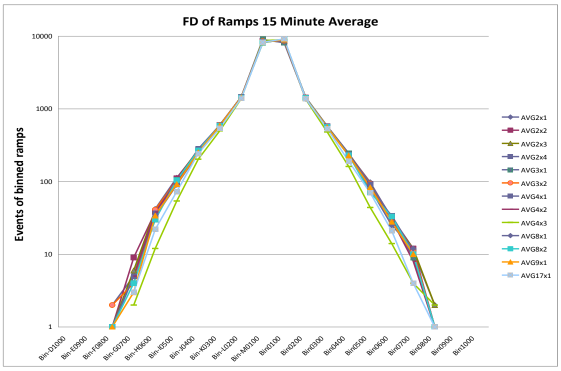
Figure 5: Averaging in space clearly reduces higher ramps. While we see 1 second ramps up to 900 Watt/sqm for a single sensor, averaging 3 or more of the 17 sensors the maximum ramp is below 500 Watt/sqm.

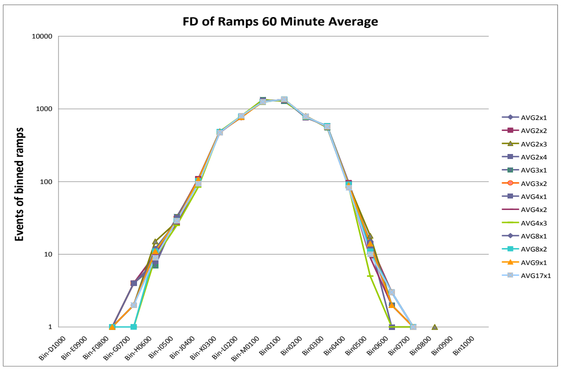
The next step of the analysis was the evaluation of the combined effect of averaging in time and space. The following figures show the results for 10 second and 60 second and 10, 15 and 60 minute time interval. The different lines in each graph explain the behavior of average of two sensors (AVG2xN), average of three sensors (AVG3xN), average of 4 sensors (AVG 4xN) and the results for averages of 8, 9 and 17 sensors. While we still see clear differences in the behavior at 10, 30 and 60 second time interval with the different number of sensors, at higher time intervals there is no difference visible.











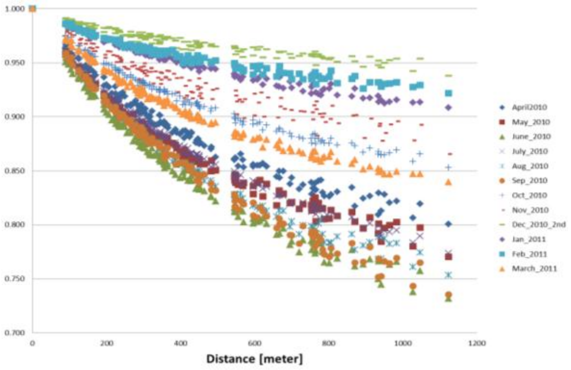


Figure 7: Monthly linear cross correlation of the 17 sensors within the 1km x 1km.

4.2 Grid Impact Results

We analyse two feeder areas using the software SynerGEE Electric. Model is a steady and pseudo steady state distribution model. Can input steady state time steps over a time period. Dynamic voltage doesn't impact the tap changer due to the 20 to 30 second delay. Two ways of analysing – first looking at the actual simulation over 24 hours. Second looking at the voltage over distance analysis and comparing to the size of tap changer voltage band and the rules of thumb.

Application of the variability analysis data

Tap changer cycling is defined as the transformer tap position increasing or decreasing a number of times, greater than the normal mean number of operations. Interconnection analysis can consider PV fluctuation as a continuous variation throughout the daytime period or the voltage at the point of interconnection with the site cycling from full on to full off condition. Steady state and pseudo dynamic analysis can fully quantify if the on/off behavior is representative, or variation throughout the day should be considered.

Tap changers alter the voltage at the substation source to the feeder depending on a measured value of voltage. The example transformer on average performs 5 operations a day. If the number increases by 1 or 2 operations based solely on PV operation, this analysis considers it a limiting factor for PV installation.

Operations and measured evidence recently shows this tap changer was now operating more frequently as the PV levels increase. Effects of tap changer cycling can result in life reduction for transformer, localized heating and wear on the tap changer parts. While the lifetime of the particular tap changer is not analyzed in this study, if a 2 position increase was seen throughout the year this represents a 40% increase in operation times (above mean).

This analysis and comparison to measured data enables a greater understanding of these impacts on a steady state and transient level. Switching impacts are decoupled from irradiance fluctuations. Short term and long term impacts are validated using the steady state SynerGEE model of the HECO feeder of interest. Future impacts can now be determined as PV generation increases and the results extrapolated to quantify lifetime reduction.

A clear or 'sunny' 24 hour period and a cloudy day (represented as April, from the 17 sensor network) is initially considered and report, followed by a distance from substation analysis for varying PV penetrations cycling from full on to full off conditions. In these scenarios, typical load profiles are plotted. The 24 hour load profile is the same for each day, only the generator output changes. A comparison of the profiles is shown below. This data is input into SynerGEE Electric and a time sequential tap changer study is completed. Penetrations considered include 25%, 50% and 100% PV (of non coincident peak load). Peak load conditions are considered.

First, the sunny day and cloudy day on WF1 for only the existing PV over the 24 hour period is evaluated as shown below.

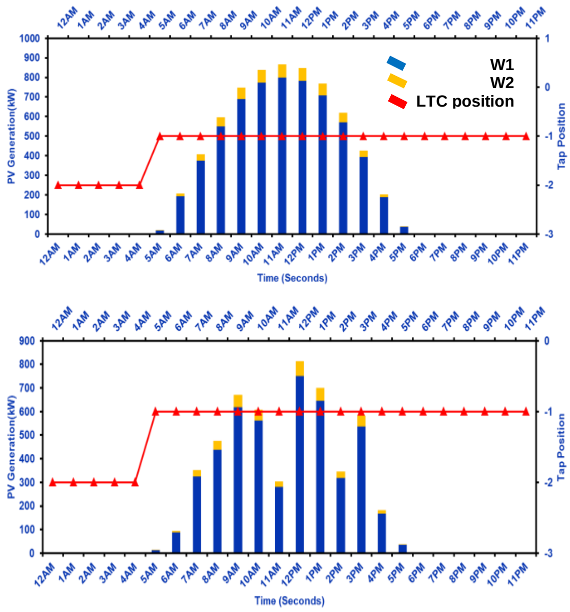
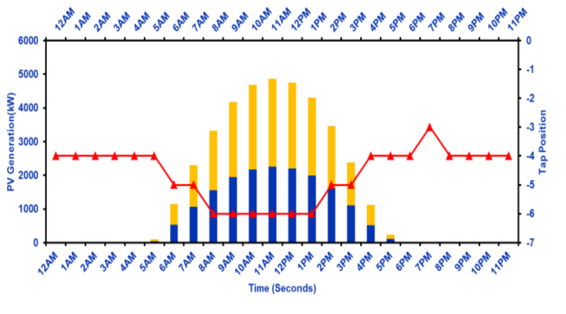


Figure 8: changer position movement with 25% PV on a sunny (upper graph) and cloudy (lower graph) day on WF1

The second scenario considers a clear and cloudy day with 50% of peak potential PV.



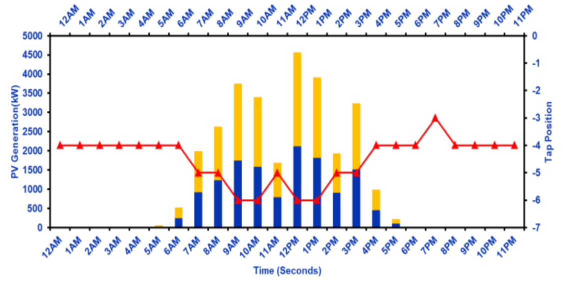


Figure 9: Tap changer position movement with 50% PV on a sunny (upper) and cloudy (lower graph) day on WF1

Finally, the 100% PV penetration and a cloudy and sunny day on WF1 is evaluated.

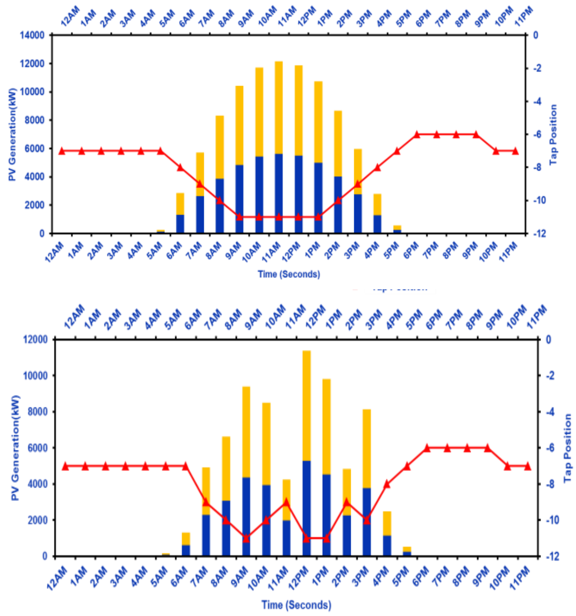


Figure 10: Tap changer position movement with 100% PV on a sunny and cloudy day on feeder1

As the PV penetration increases on these variable days, the number of tap changer operations increases from a minimal amount (5) on a clear day with existing penetration; to 2 additional steps (7 total) with 50% penetration; to approximately 4 (9 total) additional operations with 100% penetration. The increase in operations is midday (peak generation time) and during the ramp up and ramp down periods of the PV. At 50% penetration there are 7 operations on a sunny day due to increased ramp up and ramp down periods, this is increased to 9 with variable cloud cover.

While in other studies, a limit for PV penetration is presented, tap changer cycling is a longer term impact, with an increase in operations resulting in mechanical stresses and decreased equipment lifetime. Mitigation strategies for this impact include curtailment at high variability periods, and localized energy storage. A penetration limitation for this feeder, for tap changer cycling is based on the level of PV, during a high variability period that causes the number of tap change operations to move above 5. This limit may be reduced with further 20 second time step analysis.

The benefit of including this analysis in standard interconnects is tap changing impacts are better quantified, and HECO can plan for an increased equipment replacement schedule or appropriate these costs to the parties responsible. High fidelity irradiance data is necessarily to quantify these impacts. Data must be recorded at the fidelity of the shortest time delay of impacted equipment, in this case the LTC with a delay of 20 seconds.

4.3 Visualization and Presentation of Results

Importance of visualization to grid operators

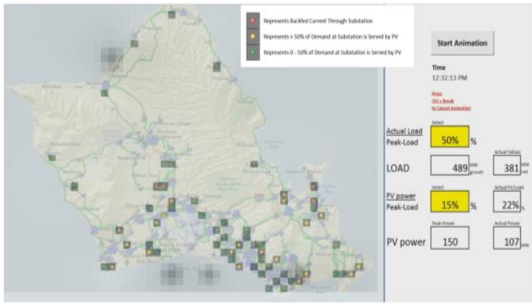


Figure 11: Analysis of the influence of variable solar radiation input to the nodes of the distribution grid at 15% penetration of PV. Yellow nodes indicating 50% of local load covered by PV, red nodes indicate backfed current.

5. CONCLUSIONS

Variability of the solar resource in Oahu is evaluated using a 17 sensor grid network in the southern part of the island. The value of measuring data at various time intervals and spatial averaging is evaluated. Some key findings include, there are clear differences in the irradiance behavior at 10, 30 and 60 second time interval with the different number of sensors, at higher time intervals there is no difference visible. Variability reduces spatially with the averages of 1 to 17 sensors, but the change is not linear. The preliminary impact of the variability on OLTC operations is evaluated in a grid simulation environment and indicated the variable resource could increase number of operations. The OLTC analysis requires further detailed investigation and research of failure mechanisms. Alternate reasoning for increased tap changer operations should be considered.

The investigations on the variability of the solar resource improved the under-standing of high penetration of PV and impact on timeframes of sensitivity to the grid. The results will be further used for grid planning, controls and informing adaption of operations and local automation logic at the distribution level as part of transforming the legacy system toward a smarter more informed grid.

6. REFERENCES

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